SUPERCRITICAL

SCOTTISHPOWER

PROTON VENTURES

April 2023

GreeNH$_3$

Executive Summary

A Hydrogen Supply 2 Competition Study

Department for Energy Security & Net Zero

GreeNH$_3$ - Green Ammonia

The Problem: Today, ammonia (NH3) is responsible for 43% of the world's grey hydrogen production and is essential for feeding the world's population through its role in synthetic fertiliser production. This market alone is responsible for ~500 million tCO2e/annum, approximately 1.8% of global emissions and it needs to be decarbonised to achieve net zero in the sector, helping the UK reach its 2050 carbon net zero goal.

In the near future, green ammonia has the potential to play a crucial role in facilitating the transport of renewable energy or as a zero emission fuel itself. With an energy density ~3x greater than compressed hydrogen and an existing distribution network, ammonia is considered as a medium for global transportation of green energy and plays a leading role in enabling the hydrogen economy.

The Opportunity: The green hydrogen and ammonia market is dynamic and is in its infancy relative to the century old, established grey ammonia market. There is huge potential to decarbonise the existing ammonia use markets as well as disrupt and decarbonise markets that have not traditionally used ammonia. IRENA predicts that ammonia production will more than triple by 2050, with more than 80% coming from renewable energy sources as seen in Figure 1.

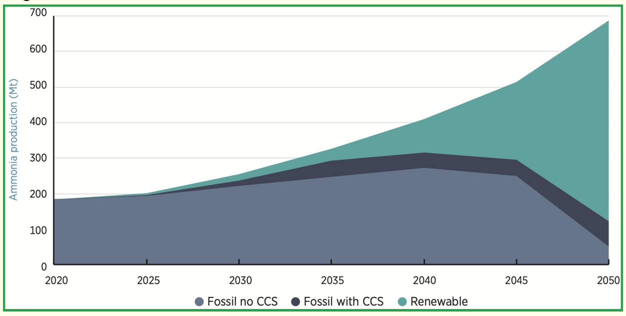

Figure 1 - Expected ammonia production capacity up to 2050 for IRENA's 1.5C scenario - IRENA, 2019

The price chart for ammonia shown in Figure 2 is historical grey ammonia production processes and incumbent demand centres (fertiliser). It demonstrates the potential for disruption in price given grey ammonia is tied to the natural gas price. Going forward, with green ammonia offering new value in its ability to fuel and to transport renewable energy, existing price points and accepted costs should not be taken as fixed. With over 30 certification schemes developed for distinguishing green hydrogen and ammonia and grey, a higher value is likely to be realised for green.

ScottishPower is exploring the export of green hydrogen and ammonia from the UK and taking steps to identify and develop the most cost-effective ways of distributing green hydrogen. Investment of time and resources to the GreeNH3 project through to the demonstration phase reinforces the commitment to the long term improvement of the hydrogen value chain.

ScottishPower, industrial partner to the project, launched their green hydrogen business in 2021 and aims to have more than 1,000 MW of green hydrogen capacity installed in the next decade. This includes a project at their onshore wind farm at Whitelee near Glasgow, where the focus is on

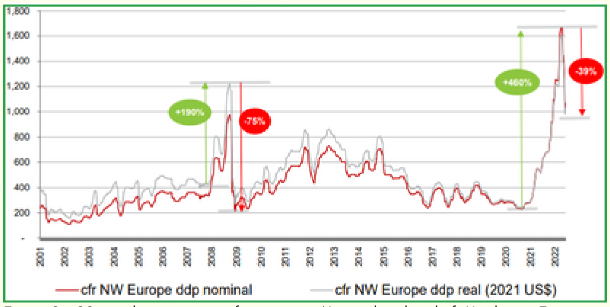

Figure 2 - 20 year historic price of ammonia - Nominal and real cfr Northwest Europe ddp, 2021-2022, ($/tonne) - IHS Markit

providing hydrogen for heavy transport and heavy industry and at Cromarty Firth (near Inverness) where the intention is to provide hydrogen initially for use in distilleries. More broadly, Iberdrola recently commissioned a facility in Barcelona to provide hydrogen for the city's bus fleet and a project to decarbonise fertiliser production in Puertollano, Spain, through the supply of green ammonia.

The Project: The GreeNH3 (Green Ammonia) project explored the feasibility of Supercritical's green hydrogen producing system integrated into a traditional Haber-Bosch ammonia synthesis loop, designed by Proton Ventures, to produce green ammonia at both a demonstrator and commercial scale. **The commercial GreeNH3 system will be fed by air and water and powered by energy from renewable sources to produce green ammonia.**

The consortium aims to produce high-purity (99.999mol%) hydrogen >200bar for direct use in ammonia synthesis (99.9wt%). Demonstrating hydrogen delivery at this purity and pressure also facilitates translational benefits to multiple sectors for green hydrogen, surpassing Grade D under ISO 14687, making it suitable for fuel cells and the majority of other applications.

The study leans upon Supercritical's proprietary electrolyser which can minimise cost and waste through its ultra-high system efficiencies. This patented novel approach removes the need for a membrane, enabling higher electrical efficiencies, with extended lifetime expected. Its membraneless design is uniquely positioned to exploit high pressure, intermediate temperature conditions, offering benefits including complete bubble removal, accelerated kinetics and rapid mass transfer. Producing hydrogen at the pressure that the ammonia industry needs; greater than 200 bar. In addition, at the end of life of an asset, Supercritical will be the only electrolyser that is almost entirely recyclable and have no "forever chemical" usage, maximising return on valuable commodity materials and being truly environment first.

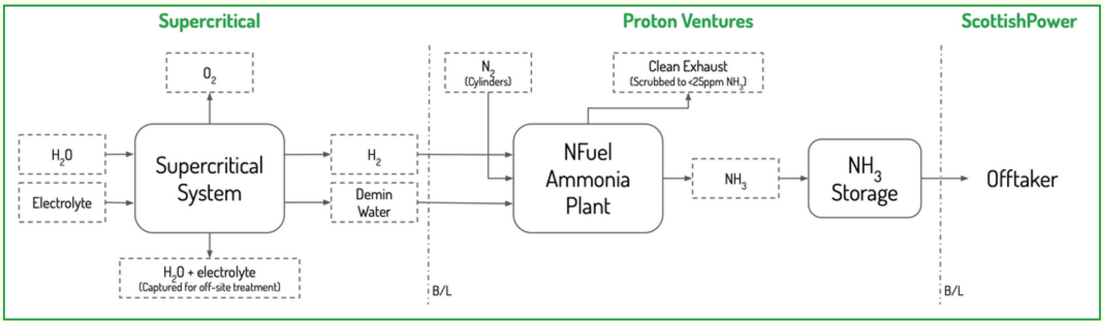

Figure 3 - GreeNH3 block flow diagram

$GreeNH_3$ Findings

LCOH200 and LCOA: The levelised cost of hydrogen (LCOH) is a term commonly used to compare different hydrogen generation technologies. It is often unclear as to whether things like water purification costs or compression costs have been included and to what pressure the system delivers the hydrogen. In this study, the levelised cost of hydrogen delivered at 200bar of pressure, LCOH200, and the levelised cost of ammonia (LCOA) have been used. The study includes costs from water purification all the way through to high pressure hydrogen and ammonia delivery respectively. A number of scenarios as defined in Table 1 were considered, with the 'Other Electrolyser' being of a PEM technology basis.

The GreeNH3 study, with full results presented in the published GreeNH3 Hydrogen Supply 2 Competition report, concludes that commercial deployment of Supercritical's electrolysis technology for high pressure, ultra-efficient hydrogen production is feasible for green ammonia production with continued development.

Table 1 - Deployment scenarios explored in the commercial model

Deployment Scenario	Ref
Other Electrolyser - UK grid only	A0
SC with UK grid only	A1
SC with solar PPA	A2
SC with offshore wind PPA	A3
SC with solar and offshore Wind PPA	A4
Other Electrolyser with Solar and offshore Wind PPA	A5
SC with Battery, offshore wind and solar	B1
SC with Compressed H2, wind and solar	B2
Other Electrolyser with Compressed H2 with wind and solar	B4

Supercritical's **LCOH200 is predicted to be 35% lower** than current incumbent technologies at commercial scales, resulting in a **21% drop in LCOA** for the modelled integrated ammonia production. Based on emissions and contained carbon, it is estimated that a **reduction of 24.2 - 35.2 MtCO2e/year compared to a polymer electrolyte membrane (PEM) electrolyser** and 170.1 MtCO2e/year compared to SMR for a given commercial plant of 43,000 kgH2/day (0.47 TWh/annum) output could be achieved.

Considering commercial ammonia production; pressurised hydrogen delivery enables the H2/N2 feed compressor to be bypassed, **reducing the feed compressor capital cost by a factor of 10 and its duty by a factor of 4**. Heat integration between the hydrogen and ammonia plant is not considered likely to be economical at scale and is not considered for early demonstrations.

Supercritical will continue to overcome the challenges of managing hazards and timelines with ambitions to scale output of the technology to **GW scale by 2030**, with potential to bring 5.6 TWh/annum of new green H2 production to market. With this, it is predicted that a minimum of **150 direct jobs** will be created and an order of magnitude more in the supply chain of goods and services.

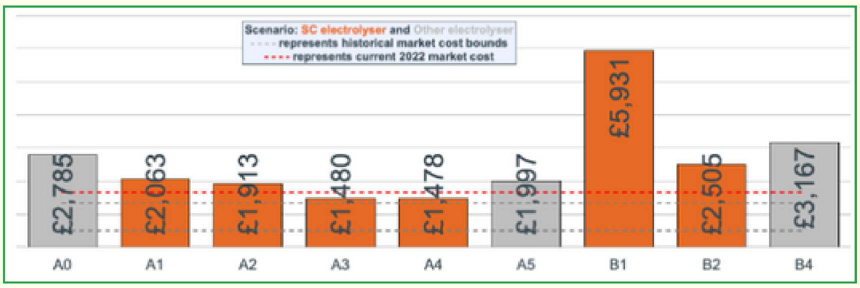

Figure 4 - LCOA per tonne of ammonia for different scenarios modelled

Table 2 - Scale up comparison vs counterfactuals

	SMR	PEM	SC
Lifecycle Greenhouse gas emissions (kgCO2e/kgH2)	11.9	2.6-3.3 (assuming renewables)	1.5 (assuming wind)
Approximate Efficiency kWh/kgH2	50.8	55.5 (60% LHV in stack)	39.2 (85% LHV in stack)
Core materials	Concrete, Steel	Steel, Titanium, PFSA membrane, Pt, Ir, Concrete	Steel, Inconel, Concrete
Ease of integration with Haber-Bosch	Low Pressure H2 Delivery	Low Pressure H2 Delivery	High Pressure H2 delivery (2-4 kWh/kgH2 benefit)
Ease of maintenance	Shutdown required but proven high reliability 90%+	Modular	Modular
Lifetime (hours)	175,000 20 years	80,000	100,000
Fugitive emission risk	Yes (CH4 GWP of 27-30)	Yes (H2 GWP of 11±5)	Yes (H2 GWP of 11±5)
End of Life	Largely recyclable	Recoverable PGM however PFAS forever chemical concern	Largely recyclable ~ 30% cost recovery expected

Supercritical Electrolyser Technology Benefits

Green Hydrogen

- Supercritical's (SC) technology can operate at high electrical efficiencies due to its operating conditions and unique membraneless design, **minimising waste, minimising cost**
  - Intermediate temperatures improve the kinetics
  - High pressures remove bubbles
  - Membraneless design minimises ohmic resistances in the cell
- Other electrolyser's inefficiencies become SC's efficiencies - SC benefits from the heat generated through electrical inefficiencies, **minimising waste, minimising cost**
- High current densities can be achieved by exploiting the bubble-less nature and high mass transport rates of the supercritical fluids, **minimising footprint, material requirements and CapEx and maximising output**
- SC delivers both hydrogen and oxygen across the battery limit at 220 bara - reducing the need for expensive and higher risk compressors, **minimising capital cost and increasing uptime**
- Operates with **zero scope 1, and scope 2 emissions** when exclusively supplied with renewable power
- Operating conditions drive materials of construction towards high performance nickel alloys for the electrolyser, this can result in a higher capital cost per unit mass of material needed, however this is offset by excellent anticipated in-life durability, high current densities (minimising size of unit) and high recovery of materials at end of life, resulting in a **leading levelised cost of pressurised hydrogen**
- Unparalleled in life reconditioning capability and end-of-life recycling capabilities - given no membrane, no PFAS (forever chemicals), all metal design, the SC electrolyser can be almost entirely recycled ensuring minimal negative effect on the environment in addition to its zero carbon operation capability, **putting the environment first, optimising material utilisation and minimising cost**

Green Ammonia at Scale

- Preferred 'always on' operation fits perfectly with existing, established ammonia synthesis processes, **minimising additional development costs for the ammonia plant and maximising integration opportunities**
- **99.999mol% High Purity** Hydrogen delivered at 220 bara negates the need for hydrogen compression into the ammonia synthesis loop, **minimising cost and electrical duty**
- **High pressure, high value oxygen by-product** can be used
  - As a feedstock to a neighbouring facility (nitric acid for example)
  - As a supply to enable oxyfuel combustion for cleaner heat generation
  - To power equipment in the ammonia plant such as the recycle compressor through means of turbo-expansion
- SC's heat and oxygen availability also make it well **suited for downstream nitric acid processes** where ammonia is oxidised.

Advancing this technology has the potential to create jobs, reduce carbon emissions, and advance sustainable practices in the transportation sector. The GreeNH3 concept has the potential to create cross-sector benefits by providing a sustainable solution that can be deployed in more challenging areas of the economy, such as heavy-duty heat, sustainable fuels, and chemical feedstocks.

You can find the full feasibility study and full list of references at the Gov.uk website here.

Department for Energy Security & Net Zero

Contact Details

Supercritical
www.supercritical.solutions
contact@supercritical.solutions

ScottishPower
www.scottishpower.co.uk
hydrogen@scottishpower.com

Proton Ventures
www.protonventures.com
info@protonventures.com